National Aeronautics and Space Administration

ARRM Reference Mission
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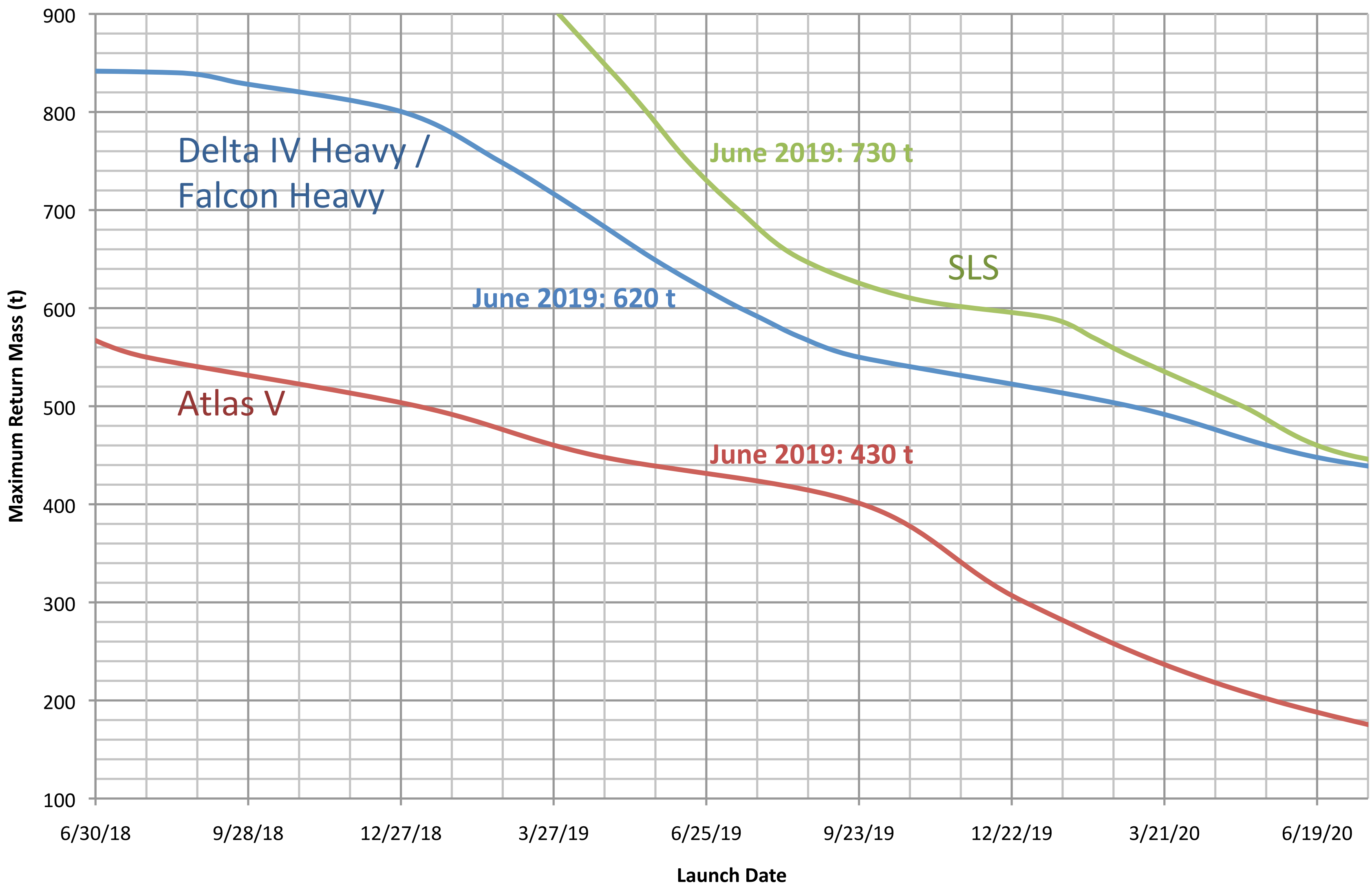
JPL, GRC, JSC, LaRC, MSFC, KSC, GSFC

ARRM Mission Constraints

- Safety:
  - Mission designed/operated to be inherently safe to planet Earth at all times
  - Vehicle will be crew safe but not human rated
- Implementation planning:
  - Assuming MCR 2/15 and launch options starting in mid-2019
  - Capable of launch on SLS, Falcon Heavy, Delta IVH and Atlas 551, assumed direct launch on SLS, FH or DIVH
  - Reasonable but bounded launch period flexibility (e.g. for 2009BD 4 months for Atlas, 18 months for SLS, FH or DIVH (compared to 21 day typical)
  - Operational lifetime at least 6 years
- Cost and cost risk:
  - Demonstrate lean development under a cost driven paradigm with acceptable technical and programmatic risk
  - SEP module/technologies are critical path with planned and funded development
  - High heritage avionics minimizes mission module cost and cost risk

2011 MD: Max Return Mass vs. Launch Date



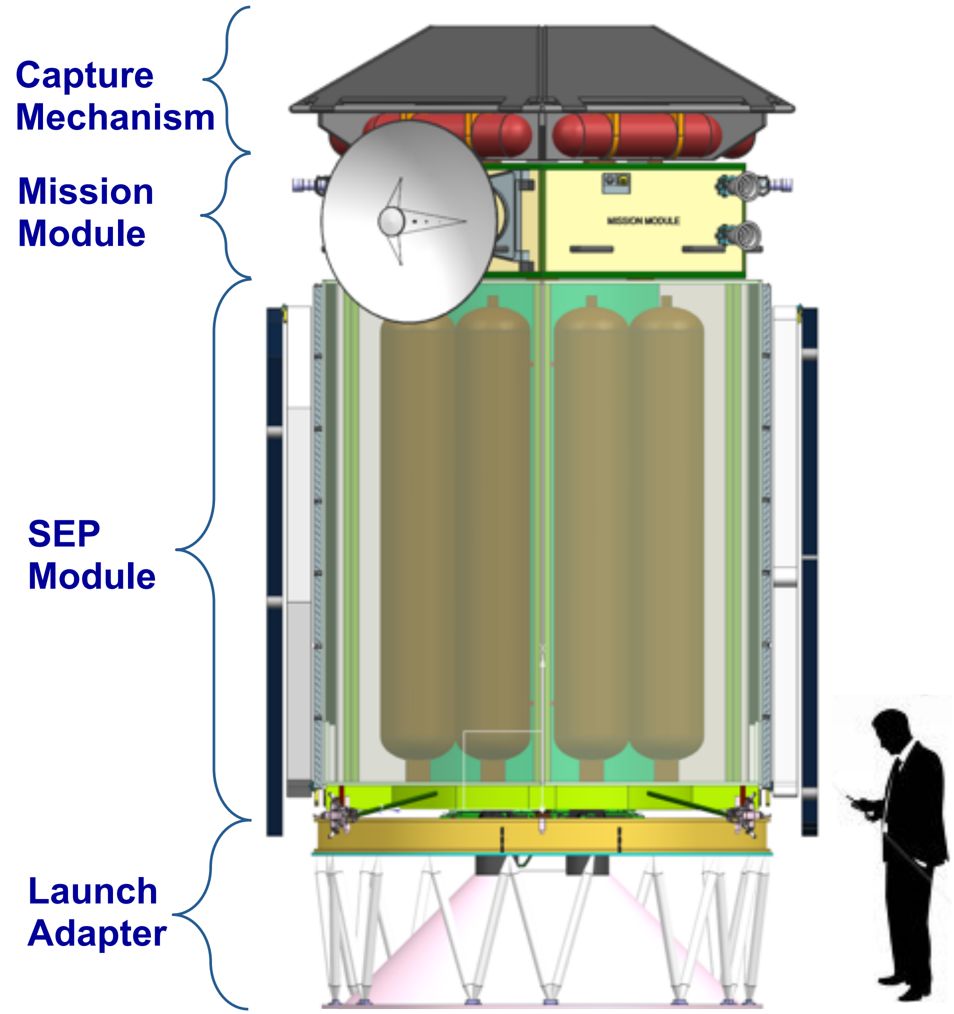
Planetary Defense Background

- Deflecting a threatening object by one Earth radii in 10 years would require a ΔV of order 1 cm/s, much less for rarer event of deflecting from a keyhole.
- Deflection Strategies
  - Impulsive
    - Kinetic Impactor
    - Nuclear Explosive (ablation or disruption)
  - Gradual, Precise Deflections
    - Gravity Tractor (GT) or Enhanced GT (EGT)
    - Ion Beam Deflector (IBD)
    - Laser Ablation, and other concepts
- Comparison of Deflection Strategies
  - Gradual technique can impart significant total impulse precisely which allows the asteroid trajectory to be accurately measured, but takes much more time than impulsive
  - IBD and GT/EGT would operate in situ but deflection capabilities are power limited and therefore, very slow. Unless there was a great deal of warning time, these are not really primary deflection techniques – more in the way of providing "trim maneuvers" following a more robust deflection technique like a kinetic impactor or nuclear explosion.
- Can reliably measure ΔV to an accuracy of <<0.1 mm/s

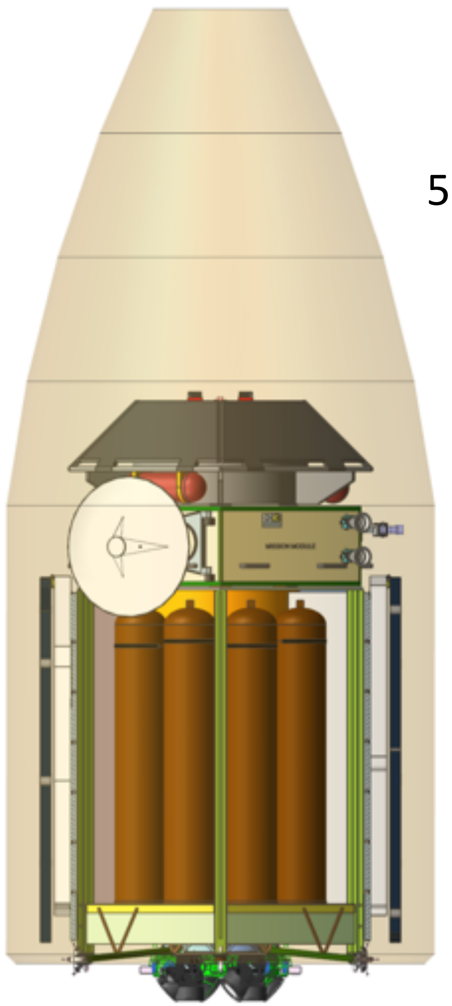
Flight System

- Key Driving Objective:
  - Minimize the cost and technology development risk with extensibility to future missions within constraints
- Architected for balanced risk and tolerance to:
  - Uncertainties in asteroid discovery and characterization
  - Transportation technology development
  - Proximity operations complexity and duration
  - Crew operations
- Flight system features:
  - Clean interfaces between SEP, Mission and Capture System modules
  - High heritage Mission Module, avionics, sensors and core SW
  - Conops validated by model-based systems engineering analysis

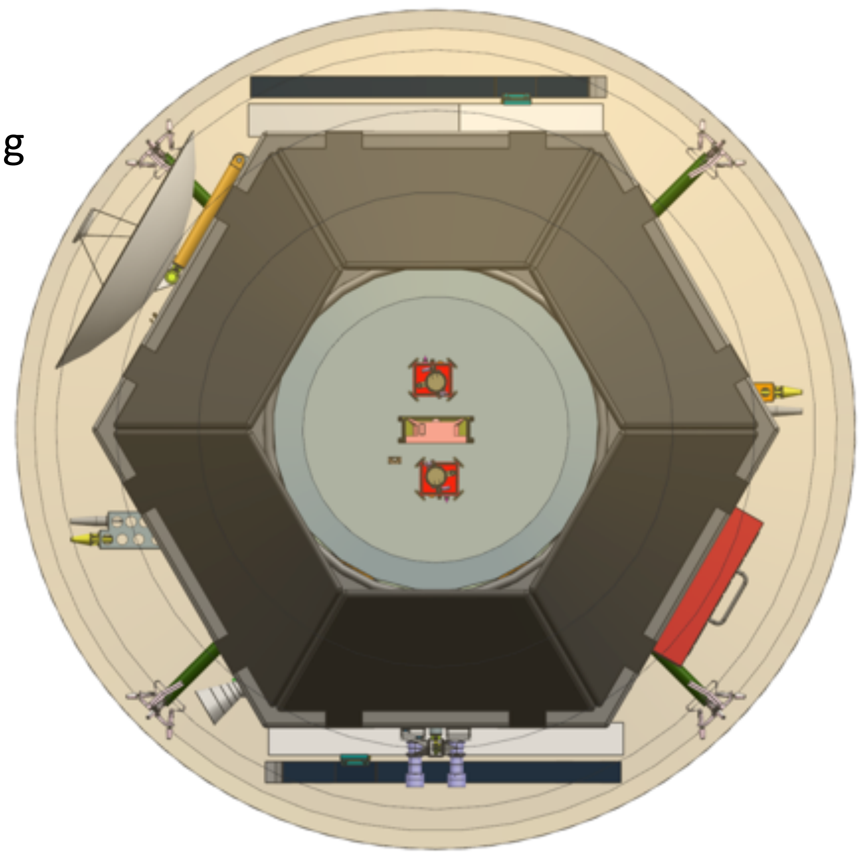
Flight system development is feasible and includes appropriate margins



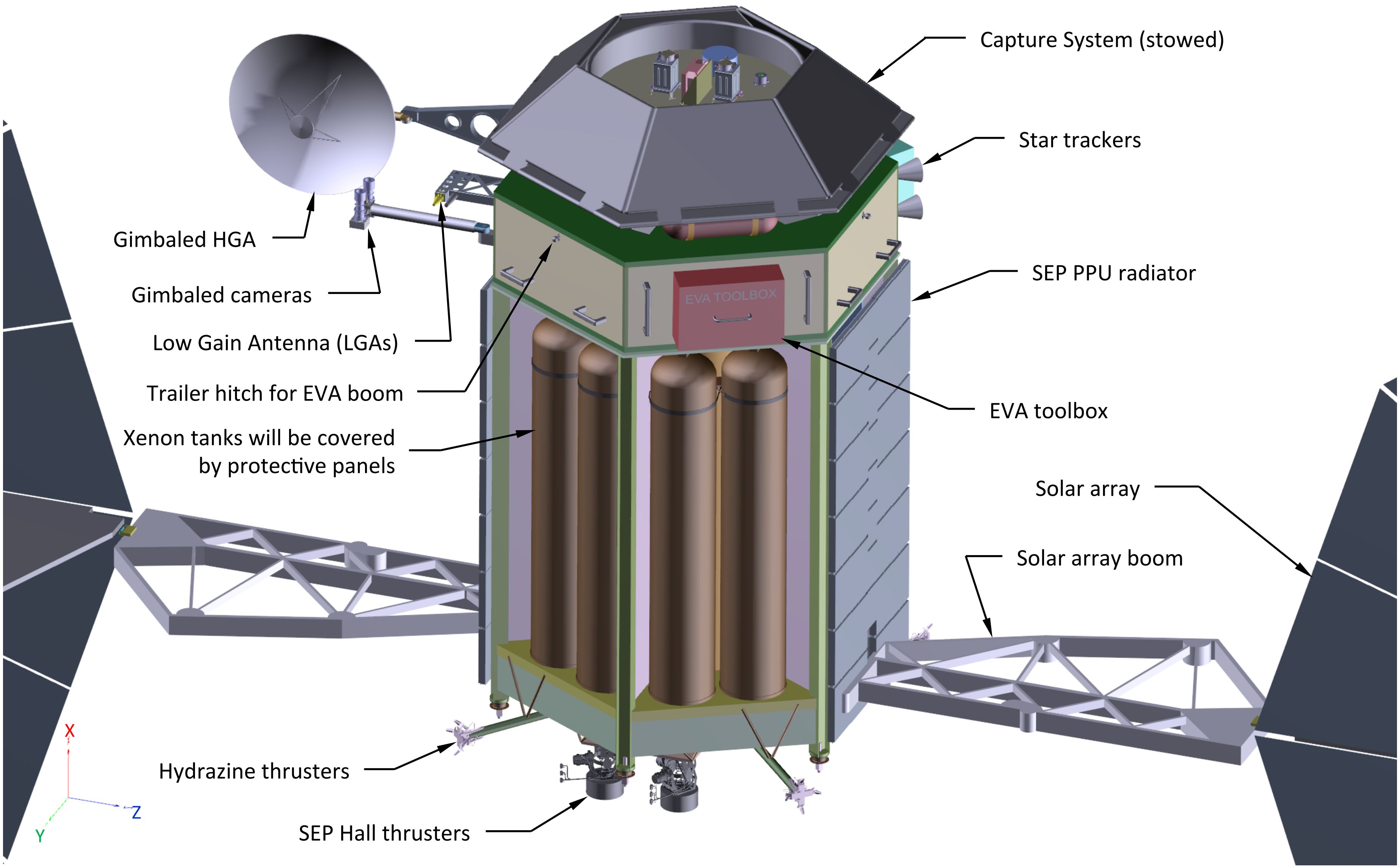
Launch Configuration



5m fairing



Deployed Cruise Configuration

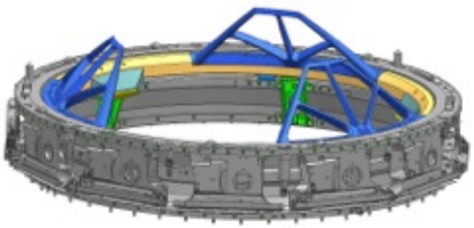


System and Mission Design Have Appropriate Margins

- System Margins (growth contingency and system margin):
  - Flight system dry mass : 43%
  - Battery DOD – Launch: 44%
  - IPS Power: 15%
  - Non-IPS power: 90%
- Capacities (including margin):
  - Xe Propellant (kg): 10,000
  - Hydrazine Propellant (kg): 200
- Analysis and simulations show adequate G&C margins
- Structural and thermal analyses show adequate margins
- Mission Design Margins
  - SEP Operating Duty Cycle: Consistent with early formulation practice, ≤ 90%, for deep space operation
  - Schedule Margin (forced coasts): Consistent with early formulation practice for deep space operation and verified with preliminary missed thrust analysis

ARRV Features for Crewed Mission

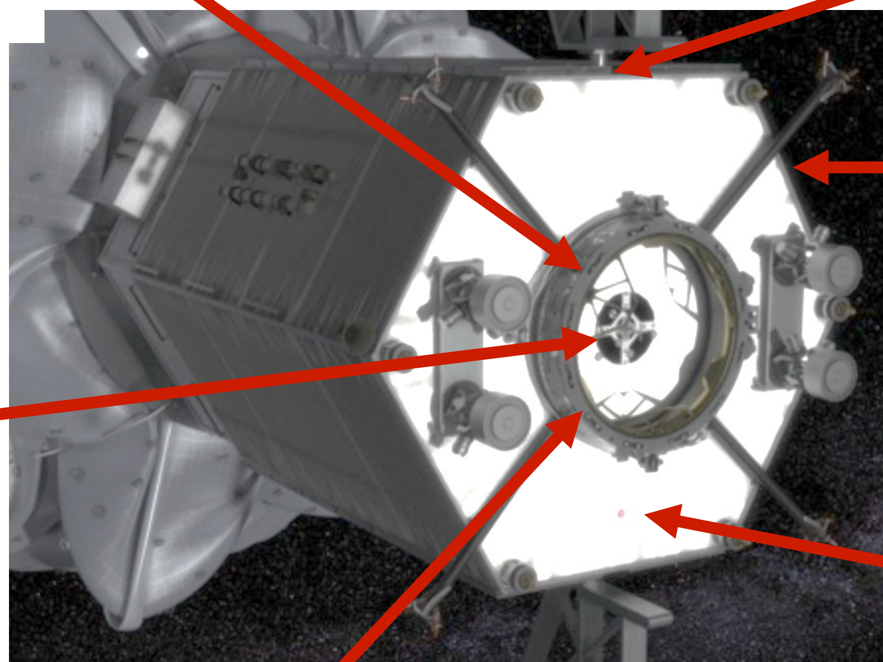
- Identified minimum set of hardware on ARRV to accommodate Orion communication, docking and extensibility



Docking Mechanism
- IDSS-compatible, passive side

Vehicle-to-Vehicle Comm
- Orion compatible low-rate S-band with transponder

Docking Target
- Augmented with features for relative navigation sensors
- Visual cues for crew monitoring



Reflectors
- Tracked by the LIDAR during rendezvous and docking

LED Status Lights
- Indicate the state of the ARV systems, inhibits and control mode

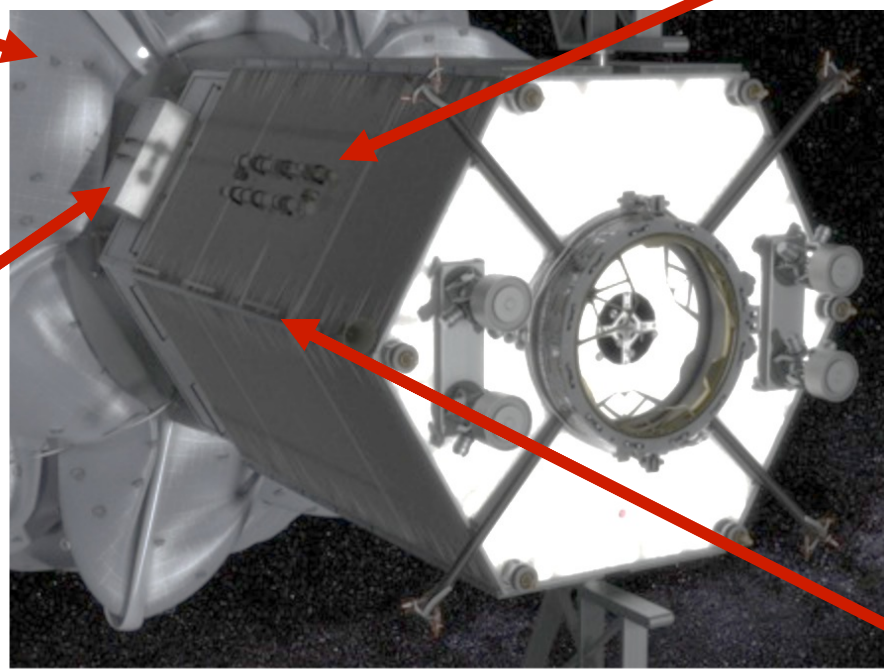
Power and Data Transfer
- Supports extensibility
- Transfer through auto-mate connectors already part of the docking mechanism design

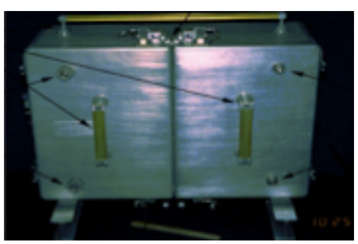
ARRV Features for Crewed Mission (cont'd)

- Identified minimum set of hardware on ARrV to accommodate Orion EVA

EVA Tether Points
- Hand-over-hand translation
- Temporary restraint of tools
- Management of loose fabric folds

Translation Boom and Attach Hardware
- Translation from Orion to ARV
- Translation from ARV to capture bag for asteroid access





Pre-positioned EVA Items
- Tool box to offset Orion mass
- Two additional translation booms

Hand Rails
- Translation path from aft end of ARV to capture bag
- Ring of hand rails around ARV near capture bag

Spin State Target Selectability Criteria

- Decision on selection of a target for capturing and returning a whole asteroid will be based on certification of the bounding size, mass and rotation state.
- For simple spinners the strategy is to match spin rate and then capture. For tumblers, design and analysis to date has focused on the hardest problem, a fast, 2 rpm, tumbler. Based on observed small asteroids (~10 m), <10% are fast tumblers.

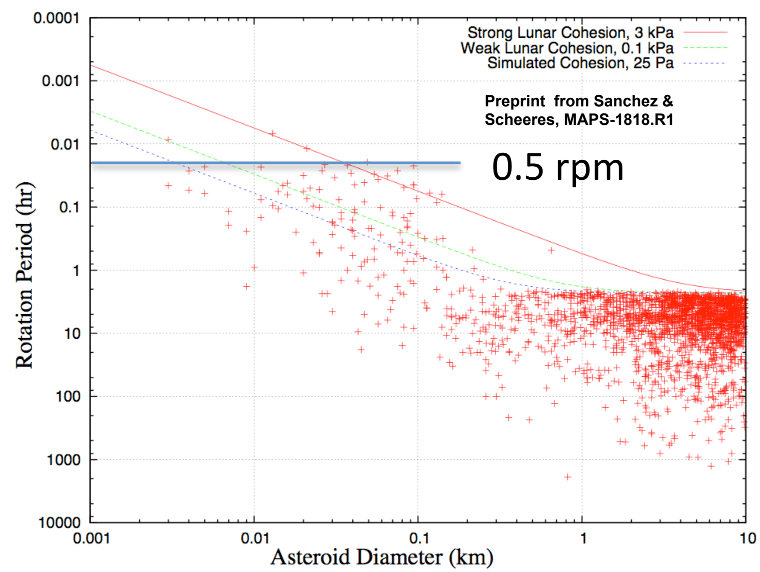
- Based on new inputs from the EVA office and the strong desire to minimize complexity and risk for the EVA phase of the mission we are evaluating revised bag designs around slower tumbling conditions, e.g. <0.5 rpm,
- Lower spin state designs will require less fabric and are expected to make access to the asteroid easier
- Option to use Ion Beam Deflection to achieve slow or slower (e.g. <0.1 rpm) is also part of the design space
- Designing to <0.5 rpm tumbler

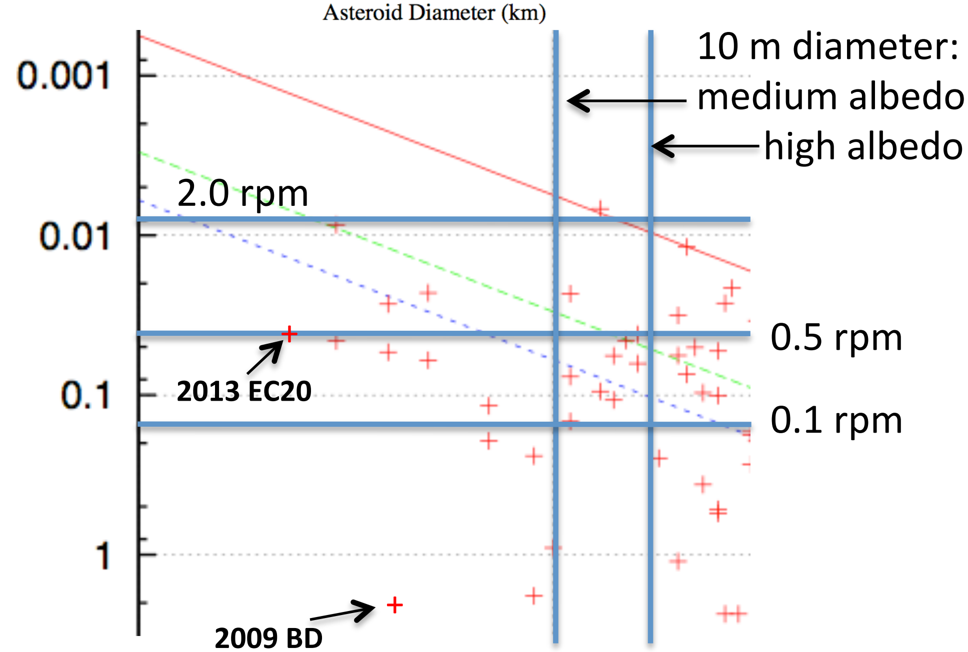
Possible Spin States

- Slow (<0.5 RPM), Simple Spin
- Slow (<0.5 RPM), Tumbling
- Fast (~<2 RPM), Simple Spin
- Fast (~<2 RPM), Tumbling

Rotation State of Small NEAs

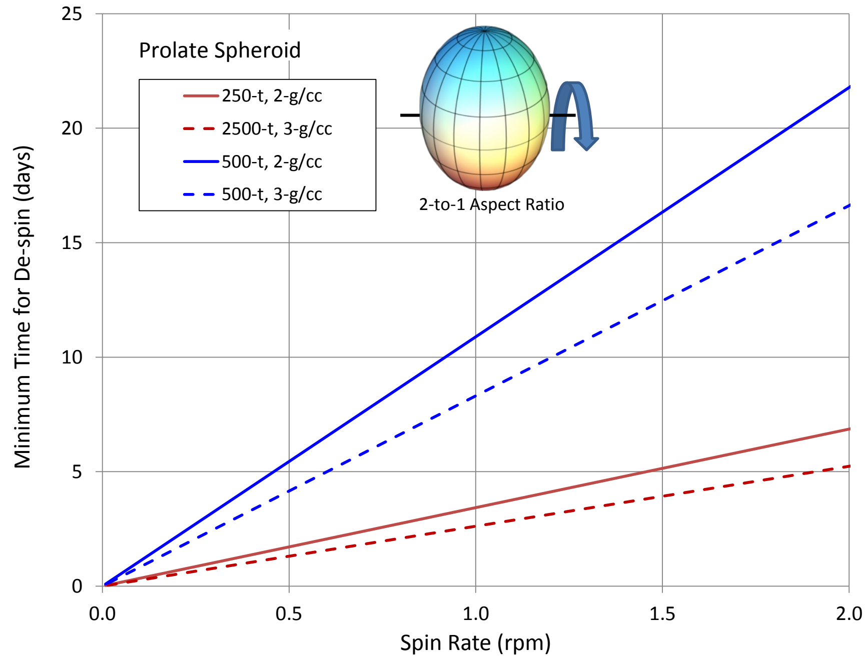
- Approximately three quarters of small NEAs observed to date are spinning slower than 0.5 rpm
  - Only one is slightly faster than 2 rpm
  - Only one known tumbler – time to relax to flat spin is short.
- Recent analysis by Sanchez & Scheeres shows that small spinning rubble piles can be held together with very little cohesion (actual properties would be measured by ARM)

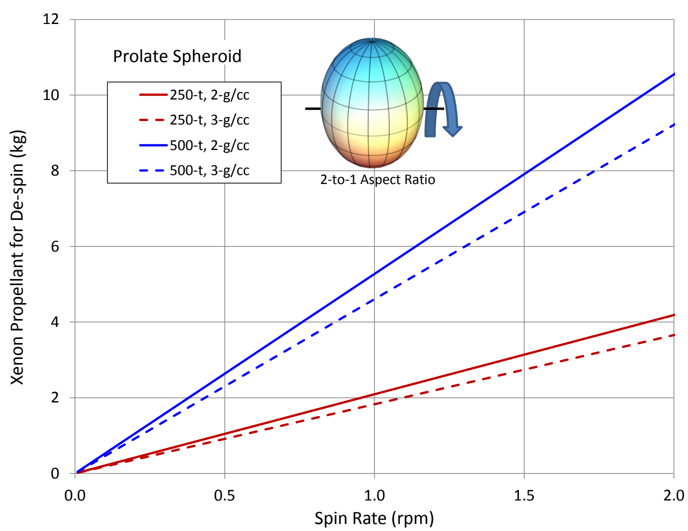


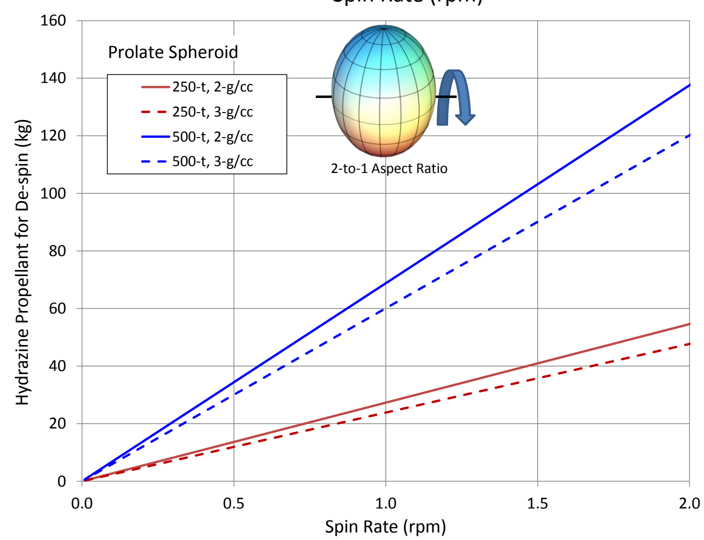


Use of IBD for Spin Down

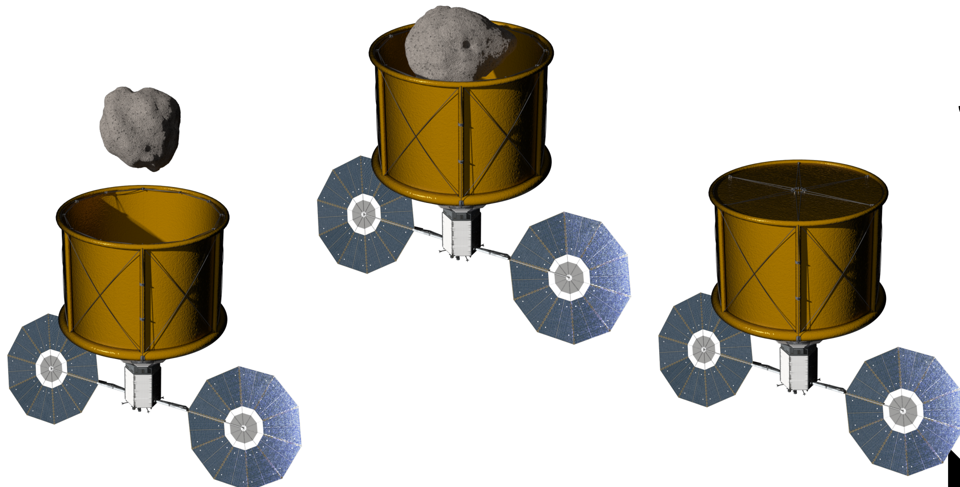
- Performed design studies of implementation IBD spin down including range of shapes, masses, etc.
- 500-t prolate asteroid can be despun from 1 rpm to 0 rpm in <6 days
  - Requires less than ~12 kg of Xe
  - Requires <70 kg of hydrazine or less



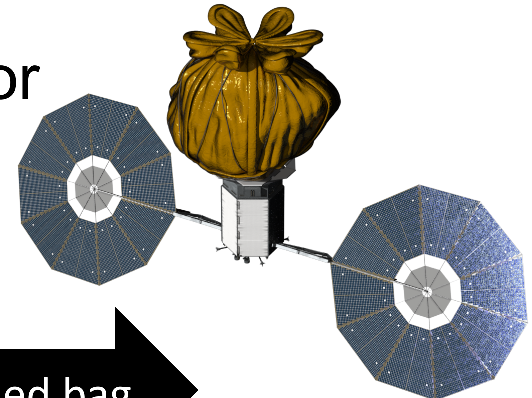




Slow and Fast Rotator Capture Sequence



Slow Rotator



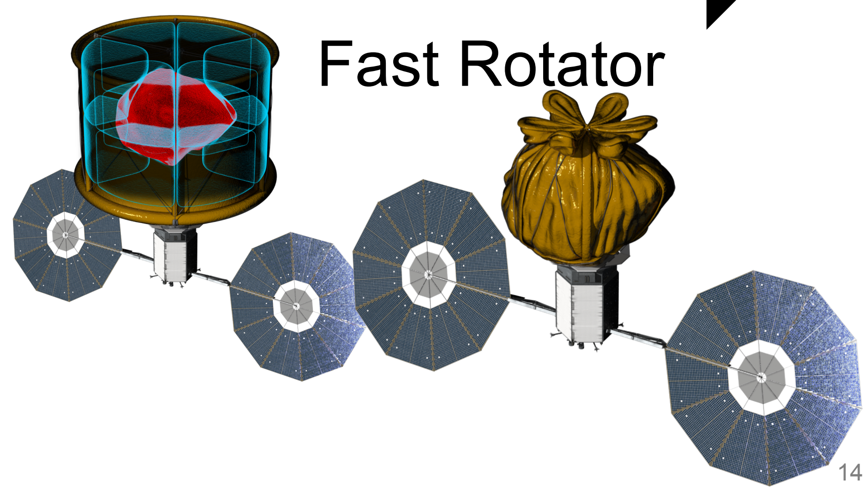
Winch closed bag

Fly S/C to position bag over asteroid, close diaphragm over top

Inflate inner bags for quick capture, winch closed bag

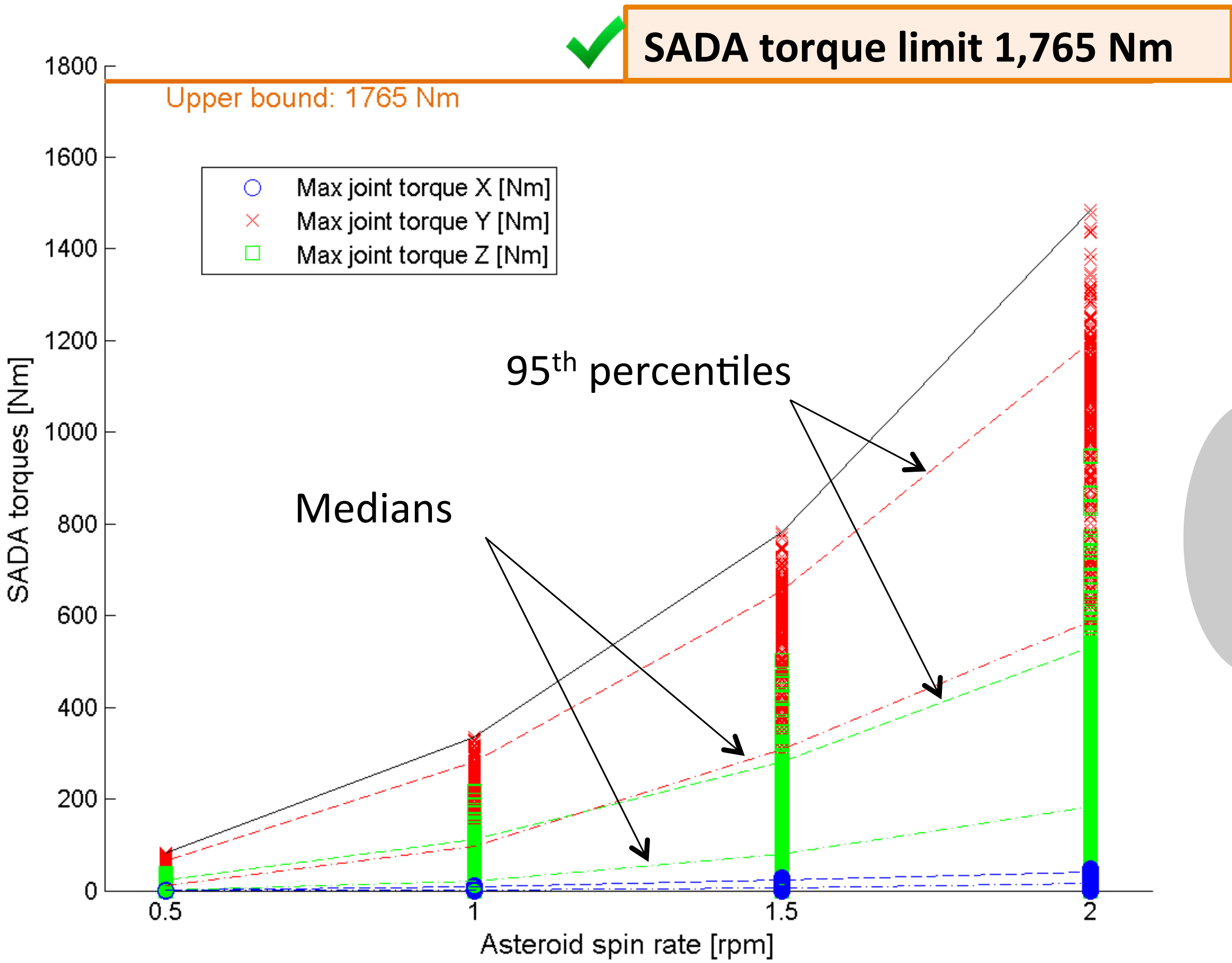
- For spinner (<2 rpm) or slow rotator (<0.5 rpm): approach, match primary spin rate, envelop, close top and winch bag down to berth, despin using RCS, re-establish full attitude control
- For fast tumbler (<2 rpm): approach, match rotation state about combined spin vector, envelop, close top, inflate pie shaped inner bags for rapid capture, despin using RCS system, winch closed bag to berth, re-establish full attitude control

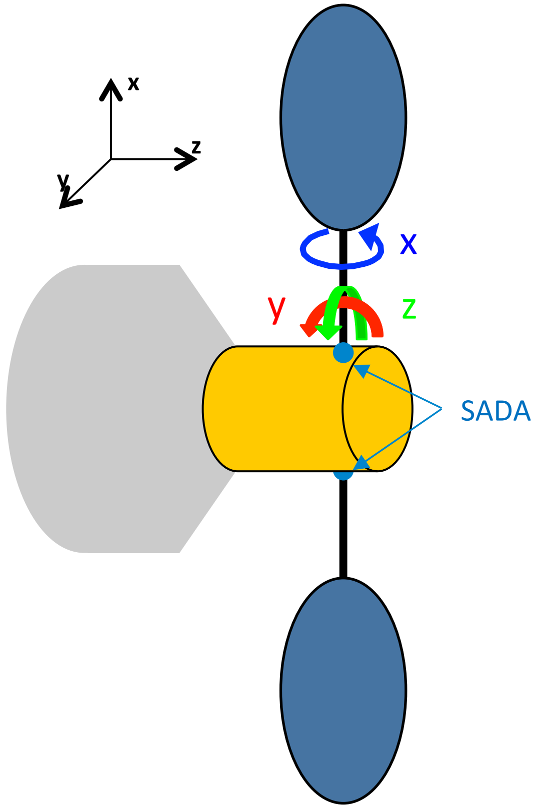
Fast Rotator



Parametric Capture Dynamics Analysis

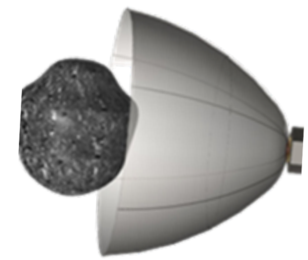
SADA and solar array torque limit is satisfied in all 3,192 cases of shapes, rotation states and rotation rates for 10 m mean diameter, 1000 t NEA

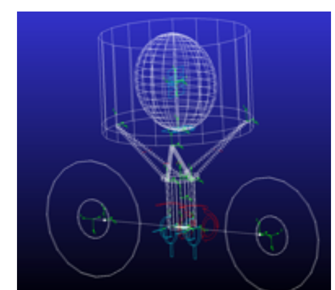




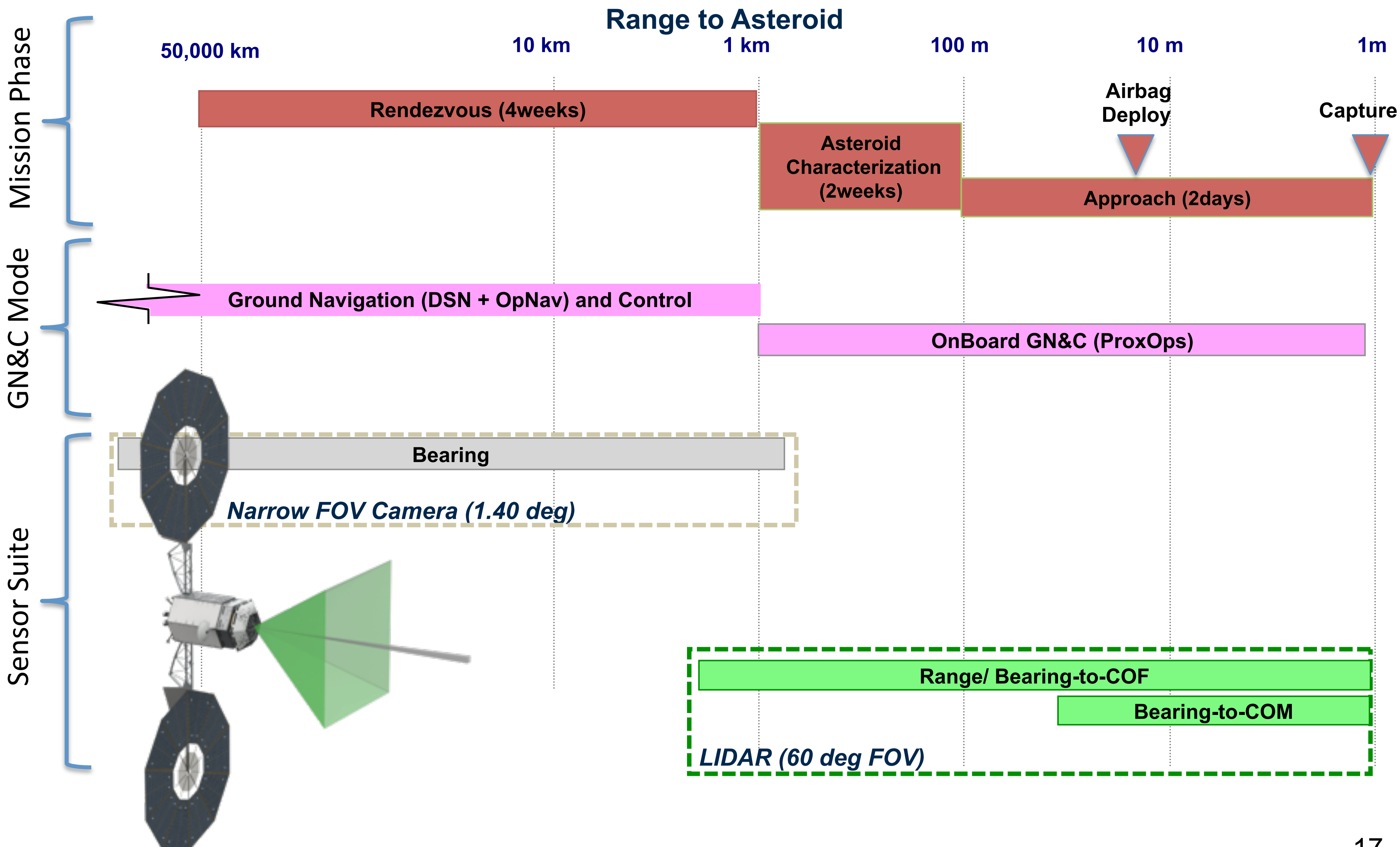
Slow Tumbler Concept Status

- Simpler design and operations
  - Berthing (docking) with a single surface bag system and winching process
  - Forces on S/C well below solar array constraint of 0.1g
- Allows a wider range of implementation options including some RFI proposed ideas that could be explored under BAA
  - Potential use of non-inflatable mechanisms concepts from a commercial vendor
- Potential to simplify fabric management for EVA operations
- Potential to provide clear bag windows (e.g. Spectra) with access ports to improve situational awareness and access
- Will be lower design complexity, lower mass, more easily tested, lower cost and lower cost risk





Reference Mission Rendezvous and Capture GN&C and Sensors



CubeSat and Science Instrument Accommodation

- Two P-Pod dispensers can be accommodated on the Mission Module to provide the delivery of the equivalent of six 1U CubeSats
  - Total mass is ~13 kg
  - Could be one 3U and three 1U; or two 3U CubeSats
- A body-fixed science instrument can also be accommodated on the Mission Module
  - 50x50x50 cm, 10 kg, 20 W, 8 Gbps max. data rate, 100 GB max. storage
  - Field-of-view provided for a radiator

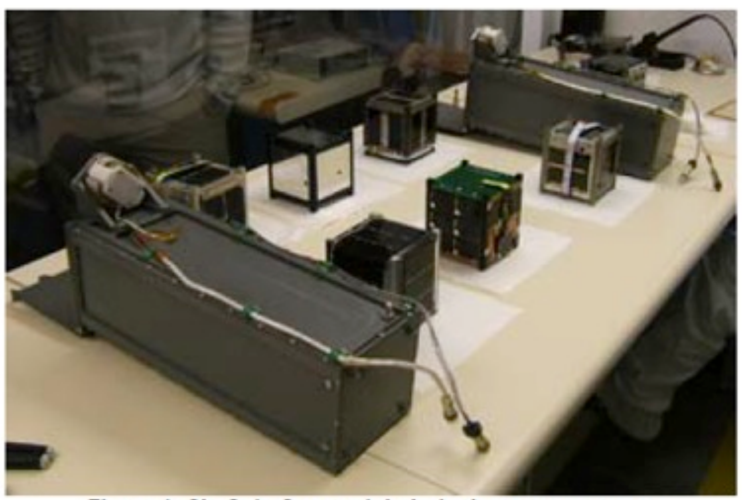
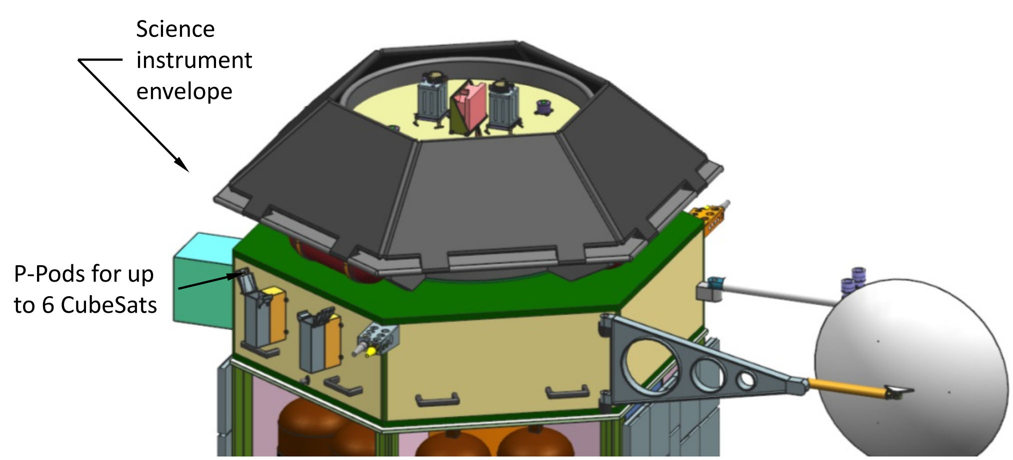
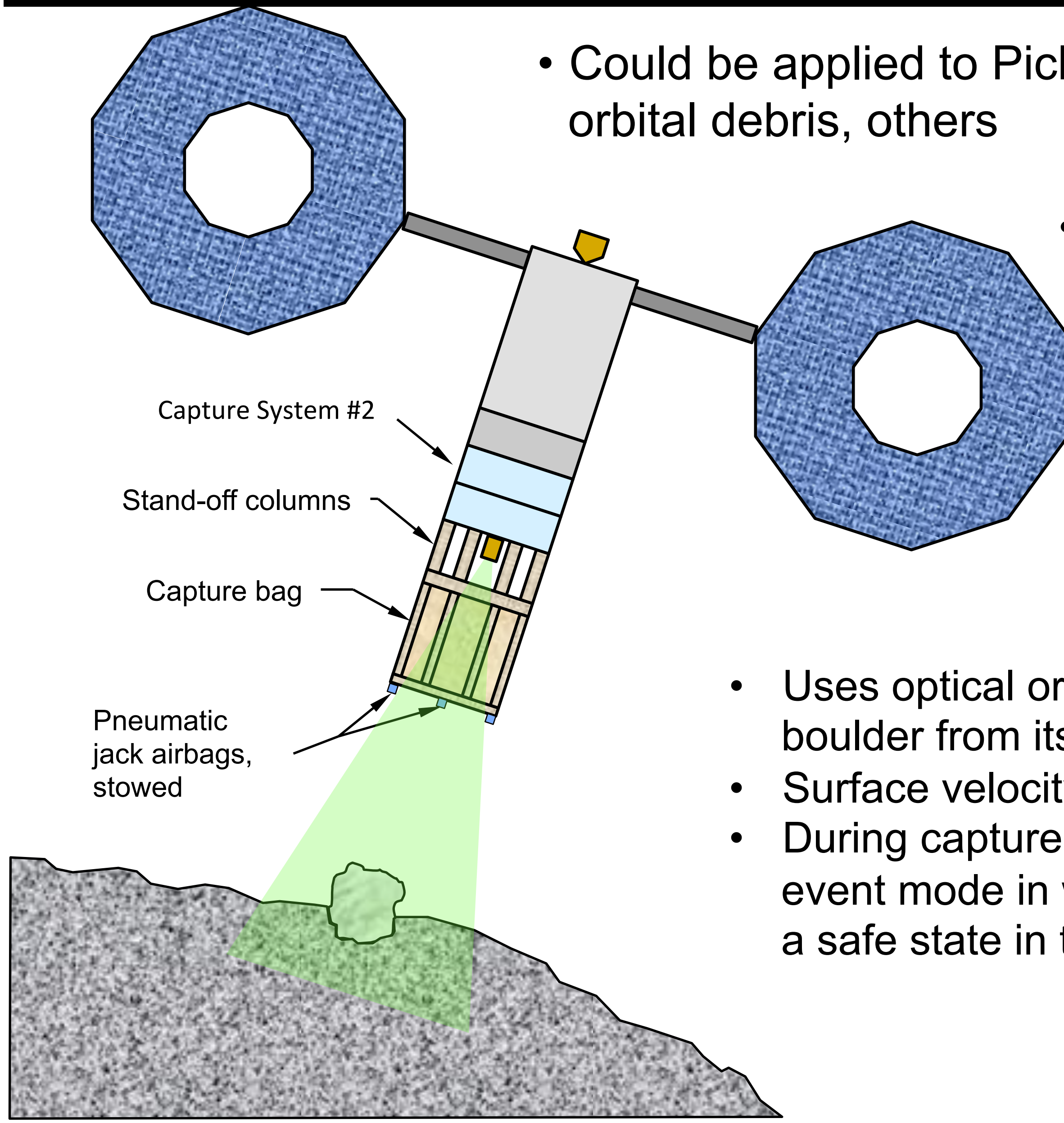


Figure 1: Six CubeSats and their deployment systems.



Capture Bag and Inflatables Are Scalable



- Could be applied to Pick-Up-Boulder (PUB), orbital debris, others

- Assumptions for PUB:
  - Boulder is partially imbedded
  - Boulder is ~ 2m
  - Boulder may not be structurally strong and could break apart at any time.

- Uses optical or LIDAR discrimination of the boulder from its surroundings
- Surface velocity precisely matched by the ARV
- During capture, system operates in a critical event mode in which the S/C control will assure a safe state in the face of most faults.

Conclusions

- ARRM reference concept is technically and programmatically feasible, and fully meets primary objectives and constraints, including cost, at reasonable confidence, at acceptable technical and cost risk
- Architecture and spacecraft elements are versatile for a range of missions and targets. Capabilities needed to return a NEA to lunar DRO in mid-2020 have been established
- Flight system options have been evaluated and a credible baseline established that meets functional objectives and is compatible with the current understanding of all possible LVs
- SEP technology options have been evaluated, and component technologies are being developed and tested
- Inflatable capture system concept meets objectives but is being further simplified to facilitate EVA ops and further reduce cost and cost risk.